

The Nature of Absolute Zero Temperature

Liu, Jerry Z. Ph.D.

ZJL@CS.Stanford.EDU

Stanford University, California, USA

Abstract

Absolute zero temperature, denoted as 0 K , is considered the lowest limit on the thermodynamic temperature scale. This theoretical value is derived by extrapolating the ideal gas law. By international agreement, absolute zero is defined as -273.15 degrees Celsius. Due to the common misconception that temperature represents the average kinetic energy of particles in a substance, the true nature of absolute zero has yet to be fully understood. In reality, temperature measures the energy released by a system, primarily associated with potential energy. Potential energy is stored between objects or particles in an interaction force, such as a chemical bond. Bonds behave like springs for energy storage. When work is done to extend the bonding space between particles, the additional energy is stored in the bond at the stretched bond length. At absolute zero, substances reach their lowest potential energy, when objects or particles are at their minimum distance within their potential force fields. In the context of Coulomb forces, electrons move to lower energy orbitals, while bonding distances minimize to their shortest length. This state is referred to as the ground state of a thermodynamic system. Similarly, in the realm of nuclear forces, elements tend to minimize potential energy between nucleons via nuclear reactions. Larger elements may undergo spontaneous fission to decrease their potential energy between nucleons while reducing nuclear size until they reach iron. Iron may be considered the ground state of elements. At the ground state, no further potential energy can be released, leading to the absence of temperature measurement, which is the nature of absolute zero temperature. On the other hand, kinetic energy tends to equilibrate with potential energy in a system. At the ground state, kinetic energy is also minimized but not necessarily to zero. For example, electrons continue to exhibit orbital motion and spin, maintaining some level of kinetic activity.

Introduction

The concept of an absolute minimum temperature can be traced back to 1665 in Robert Boyle's work, "New Experiments and Observations Touching Cold".^[1] This temperature was initially predicted through Charles's law of volume, which states that the volume of gases tends to expand when heated and is proportional to temperature.^[2-3] According to this law, the volume of gases would theoretically reach zero at a temperature of around $-273.15\text{ }^{\circ}\text{C}$, commonly regarded as the lowest possible temperature and defined as absolute zero temperature, i.e., 0 K . However, the physical nature of this minimal temperature has not been fully understood. It is often assumed that at absolute zero, the fundamental particles of nature exhibit minimal vibrational motion. Nevertheless, this notion is a misconception, as the temperature is a measure of the energy released in a system, primarily associated with potential energy, and is not fully represented by the kinetic energy of particle motion.^[4] This article seeks to clarify the physics at absolute zero.

Energy Constituents of a System

Temperature is closely related to the internal energy of substances. To grasp the connection between temperature and energy, it's essential to delve into the energy constituents within substances. Energy primarily exists in two forms: kinetic energy and potential energy. Kinetic energy pertains to the motion of objects, whereas potential energy is associated with the interactions between objects at a certain distance from each other. Both types of energy are related to forces. By definition, energy is the work done by a force on an object over a distance:

$$(1) \quad d_E = Fd_s$$

where d_E denotes the object's energy increment by a force F after moving a distance d_s in the direction of the force. For example, when the velocity of a resting object is accelerated by a force to v , the object's kinetic energy can be evaluated by integrating Equation (1):

$$(2) \quad K = \int_0^v d_E = \int_0^v Fd_s = \int_0^v mad_s = \int_0^v m \frac{d_v}{d_t} d_s = \int_0^v m \frac{d_s}{d_t} d_v = \frac{1}{2} \int_0^v md_v^2 = \frac{1}{2}mv^2$$

where K denotes the kinetic energy, m represents the object's mass, a indicates the acceleration, and v is the velocity of the object. Equation (2) represents the classical form of kinetic energy. Hence, kinetic energy exists in any moving objects and particles. Similarly, the kinetic energy of a rotational object can also be computed from Equation (1). Essentially, there is kinetic energy in any moving object, such as the moving, vibrating, or spinning of an orbiting electron.

When work is done to an object against a force, its potential energy increases, which can also be evaluated using Equation (1). For instance, an object is raised against gravity on Earth. Its increment in potential energy can be calculated by integrating the gravitational force over the elevated height:

$$(3) \quad U = \int_0^h d_E = \int_0^h Fd_s = \int_0^h mgd_s = mg(h - 0) = mgh,$$

where U denotes the increment of the potential energy of the object, m represents the object's mass, g refers to the acceleration due to the gravitational force, and h stands for the elevated height of the object. For simplicity in the above evaluation, the gravitational acceleration g is assumed to be a constant for a small elevation on Earth. For a more accurate calculation, Newton's universal gravitation law can be used for the force in the evaluation above. Expression (3) represents a simple form of potential energy increment when an object is pulled away from its attraction source. Potential energy exists in objects between an interaction force. Whenever the distance between interacted objects is extended, its potential energy is increased. Potential energy exists not only between objects in gravitational force but also between nucleons due to the nuclear force. For instance, because of the immense strength of nuclear forces, a substantial amount of potential energy is released in nuclear reactions. Similarly, various potential energies also result from different manifestations of the Coulomb force. Bond energy exists between atoms as well as between molecules due to chemical bonds and intermolecular bonds. Potential energy is also stored between nuclei and the electrons around them.

According to Einstein's theory, mass and energy are interchangeable:

$$(4) \quad E = mc^2 = K + m_0c^2$$

where E denotes the total energy in a body of substances, such as an object or a gas system, m represents the relativistic mass of the object, m_0 refers to the rest mass, c is the speed of light, K stands for the kinetic energy appreciation due to the increase in the object's speed.^[5-6] In this equation, where is the potential energy discussed above represented? They are encapsulated in the resting mass m_0 . For example, hydrogen can transform into iron through a series of nuclear fusions. As this happens, the average nucleon mass decreases from that of a hydrogen nucleon (m_h) to an iron nucleon (m_i). The energy released during this process, known as nuclear energy, arises from the potential energy between nucleons or even between sub-particles within nucleons. This energy release is proportional to the mass deficit, $(m_h - m_i)c^2$. Indeed, iron has the lowest average nucleon mass among all elements. Larger elements typically release their nuclear potential energy through nuclear fission. This phenomenon aligns with the principle of minimum energy, which is the tendency of systems to minimize their energy. This is why large rocks are more stable in valleys rather than on mountain peaks. This principle also explains why second-generation stars, like our Sun, have high concentrations of iron in their system. Given the equivalence of mass and energy as a universal law, potential energy in chemical bonds also contributes to mass. Consequently, a fully charged battery weighs slightly more than when it is discharged.

How do the various energy components discussed above influence temperature? Why are hydrogen atoms on Earth not as hot as those in the Sun? In the Sun, temperature measures the energy released from potential changes stemming from nuclear reactions. The Sun's exceptionally high temperature reflects the vast potential energy between nucleons. In contrast, the temperature of hydrogen atoms on Earth represents only the energy released during their spontaneous activities, such as electron orbital transitions and potential energy release due to the decrease of bonding space discussed later. Essentially, temperature largely depends on the type of energy source. This is evident in the temperature difference in the Sun (on the scale of $1,000,000\text{ K}$) versus in a hydrogen combustion engine (around $1,000\text{ K}$), highlighting how the force magnitude of the energy source shapes temperature.

Nuclear reactions in the Sun seem spontaneous. On Earth, however, these fusions require substantial initial energy input to initiate, whereas, natural nuclear fissions can occur without any triggering energy. Similarly, some chemical reactions require an external energy boost to start, while others can occur spontaneously. When we measure the temperature of a cup of water, the energy released is also spontaneous, primarily related to electron orbital transitions. Photons are emitted when electrons move from higher to lower orbitals. Potential energy is also stored in bonds. Additional energy can accumulate in extended bonds, like stretched springs. This stored energy can be released spontaneously when the bond length decreases, also related to electrons transitioning to lower orbitals. In the conventional sense of temperature, it typically refers to the energy released during these spontaneous processes, primarily from bonds.

While the force of the energy source determines the magnitude of the related temperature, temperature is not directly proportional to the force. Instead, temperature measures the energy released due to changes in potential energy, which does not necessarily equate to the dissociation energy between particles. Typically, the dissociation energy may be expressed in terms of the binding force between particles. In nuclear reactions, the released energy relates to the potential difference between nucleons before and after the reactions, similar to the concept of enthalpy in chemical reactions. In a system without chemical reactions, temperature reflects the energy released in physical processes, such as electron orbital transitions, primarily due to the reduction in bonding distances.

The Nature of Temperature

It is a common misconception that temperature represents the average kinetic energy of substances. As discussed above, temperature measures the energy released primarily related to the change in the potential energy of a system. However, temperature does not directly represent any particular component of internal energy. According to the study "Can Temperature Represent Average Kinetic Energy?",^[4] the influence of kinetic energy on temperature is minimal in solids and liquids. In gases, the contribution of kinetic energy to temperature can be estimated in the kinetic theory of gases. This contribution is significant in monatomic gases but diminishes in polyatomic gases. As molecules become more complex with an increased number of bonds, the kinetic energy's contribution to temperature becomes even less significant. Instead, the potential energy of bonds becomes the dominant factor influencing temperature. For example, with 25 molecular bonds in octane, the kinetic energy only accounts for about 7% of temperature changes in specific heat capacity, while the rest of the specific heat energy contributes to the changes in the potential energy of bonds.

Potential energy is stored in bonds due to the tension force between particles, much like the energy stored in stretched springs. As the space between the particles expands, more energy accumulates in the bonds. This understanding resolves a 150-year-old dilemma regarding the discrepancy between the specific heat of gases with complex molecules and predictions from the kinetic theory. Thermal expansion can be more readily explained with this new understanding: volume expansion at higher temperatures is driven by the need for extended bonding space for accommodating more potential energy, rather than the demand from particle vibrations.^[7] This explanation also addresses the challenges vibration theory faces in explaining thermal contraction, such as water reaching its minimum volume at 4°C and expanding as temperature decreases. While vibration theory predicts a monotonic volume expansion with rising temperature, the new theory relates volume changes to alterations in bonding space or structure. As the temperature approaches the freezing point, hydrogen begins to form the less compact hexagonal structure of ice crystals, similar to snowflakes, leading to volume expansion.

Another common misconception concerns phase transitions: it's often believed that latent heat is solely used to break bonds, while the kinetic energy of particles remains unchanged, keeping the temperature constant. In reality, during a phase transition, molecules gaining freedom from fixed positions in bonds leads to an increase in kinetic energy. Thus, if temperature reflects kinetic energy, it should rise. This misconception stems from a misunderstanding of temperature. With the new understanding that temperature primarily relates to potential energy, anchored by the limitation in the potential energy of intermolecular bonds during phase transitions, things become clearer. Phase transitions result from changes in these bonds, which are broken by transimpacts—impacts resulting from atomic electron transitions.^[8] The potential energy of these bonds is constrained by the intensity of transimpacts they can withstand.^[9] This effectively sets the potential level of the system, fixing the temperature during phase transitions.

When using an infrared thermometer to measure temperature, the device detects the average radiation level of electromagnetic waves emitted by a target object without even making physical contact. This radiation level corresponds to the potential energy of the target, linking temperature to the object's potential energy. Similarly, mercury or alcohol thermometers operate on this principle. As the mercury in a thermometer absorbs energy from its surroundings, its potential energy increases, leading to an expansion in bonding distance. This results in thermal expansion, causing the mercury column in the thermometer to rise. The length of this column is typically calibrated against a scale for temperature readings. In this way, these thermometers also gauge primarily the average level of potential energy.

If temperature primarily relates to potential energy, why does there seem to be a correlation between temperature and kinetic energy? When energy is introduced into a system, the potential components absorb it directly. Additionally,

transimpacts convert some of this energy into kinetic energy. Over time, the system reaches a dynamic equilibrium among its various components as well as its environment. When the influx of energy decreases, the system begins to emit more energy than it receives. This leads to a net reduction in potential energy and a loss of equilibrium with kinetic energy. As a result, impactrans convert kinetic energy back into potential energy to restore balance. In both scenarios, changes in potential energy take precedence, with kinetic energy following suit.

Temperature fluctuates with changes in the potential energy of a system. The equilibrium process creates a delusion of a direct correlation between temperature and kinetic energy, leading to the misconception that temperature directly corresponds to kinetic energy. In reality, their relationship is indirect and secondary. However, this secondary relationship breaks down when a system undergoes phase transitions at a constant temperature, where temperature becomes completely decoupled from kinetic energy.

The Physics of Temperature at Absolute Zero

Understanding the nature of temperature makes the physics of absolute zero straightforward to grasp. Temperature primarily measures the energy released from changes in potential energy. The minimum temperature corresponds to the lowest potential energy level. Absolute zero occurs in substances where electrons occupy the lowest orbitals and the distance between bonding particles is minimized. There is no transition to a lower energy state beyond this point. Without detectable radiation, thermometers would naturally register their lowest readings in the absence of electromagnetic waves. At equilibrium at absolute zero, kinetic energy is minimized, although it doesn't necessarily reach zero. This is because electrons continue to exhibit orbital movement and self-spinning.

Consider a scenario where a system is designed to exclusively emit energy through electromagnetic waves while remaining impervious to external energy input. In this setup, the system's potential energy gradually diminishes to ground level over time. Equilibrium processes, such as transimpact and impactrans, work to minimize kinetic energy. Any remaining kinetic energy, like particle vibrations, is transformed into potential energy through impactrans and eventually emitted as radiation. In this way, the system will ultimately approach absolute zero temperature.

However, these natural spontaneous processes do not necessarily ensure the minimum internal energy of a system. Within the framework of the Coulomb force, some substances may still have compounds with higher potential energy in their chemical bonds than others. This potential energy can be reduced through chemical reactions. For example, when methane burns in the air, it transforms into carbon dioxide and water, releasing some of its potential energy. In the realm of nuclear force, large elements may undergo spontaneous fission, releasing potential energy as they transform into smaller elements. However, to reach the lowest potential element, iron, some initial energy is required to initiate the nuclear reactions.

Conclusions

There are two levels at which we can consider the minimum internal energy of matter, depending on whether or not we take nuclear forces into account. Without nuclear reactions, temperature reflects the measurement of potential energy released in substances, mainly associated with the Coulomb force. At this level, the lowest potential energy is found at the ground state of all components. Consequently, absolute zero temperature is reached when electrons occupy their lowest

orbitals and bond lengths are at their shortest. While kinetic energy is minimized at this point, it doesn't necessarily drop to zero since electrons continue to move within their orbitals. This should be the state of absolute zero referenced in the context of thermodynamics. When we factor in nuclear forces, the minimum internal energy corresponds to the state when all elements have transformed into iron, after minimizing the distance between nucleons and releasing all potential energy associated with nuclear forces. In all the cases, the lowest energy level is at the state of minimum bonding distance between particles under the influence of various forces.

See Also

- [Unified Theory of Low and High-Temperature Superconductivity \(PDF\)](#)
- [Superfluids Are Not Fluids \(PDF\)](#)
- [Electron Tunnel \(PDF\)](#)
- [LK-99 Limitations and Significances \(PDF\) \(中文\)](#)
- [The Cause of Brownian Motion \(PDF\)](#)
- [The Process Driving Crookes Radiometers \(PDF\)](#)
- [Can Temperature Represent Average Kinetic Energy? \(PDF\)](#)
- [Why Phase Transition Temperature Remains Constant \(PDF\)](#)
- [Is Thermal Expansion Due to Particle Vibrating? \(PDF\)](#)
- [The Nature of Absolute Zero Temperature \(PDF\)](#)
- [Misconceptions in Thermodynamics \(PDF\)](#)
- [Superconductor Origin of Earth's Magnetic Field \(PDF\)](#)
- [Tidal Energy Is Not Renewable \(PDF\)](#)
- [How to Understand Relativity \(PDF\)](#)
- [The Simplest Derivation of \$E = mc^2\$ \(PDF\)](#)

Revision History

- [11/25/2023: Initial Post of This Article.](#)
- 04/20/2024: Reorganizing and Clarification of Some Concepts.

References

1. Boyle, R. (1665). "New Experiments and Observations Touching Cold". London: Printed for John Crook.
2. Gourgy, J.B. (1979), "Charles the Obscure". *Isis* **70** (254): 576-579.
3. Gay-Lussac, J.L. (1802), "Recherches sur la dilatation des gaz et des vapeurs". *Annales de Chimie*, **XLIII**: 137. [English translation \(extract\)](#).
4. Liu, J.Z. (2023). "[Can Temperature Represent Average Kinetic Energy?](#)" Stanford University. Archived ([PDF](#)).
5. Liu, J.Z. (2020). "[The Simplest Derivation of \$E = mc^2\$](#) ". Stanford University. Archived ([PDF](#)).
6. Liu, J.Z. (2021). "[How to Understand Relativity](#)". Stanford University. Archived ([PDF](#)).
7. Liu, J.Z. (2023). "[Is Thermal Expansion Due to Particle Vibration?](#)". Stanford University. Archived ([PDF](#)).
8. Liu, J.Z. (2019). "[The Cause of Brownian Motion](#)". Stanford University. Archived ([PDF](#)).

9. Liu, J.Z. (2023). "[Why Phase Transition Temperature Remains Constant](#)". Stanford University. Archived ([PDF](#)).